COSMOLOGY AND GRAVITATION

FROM THE EARLY UNIVERSE TO THE DARK SECTOR

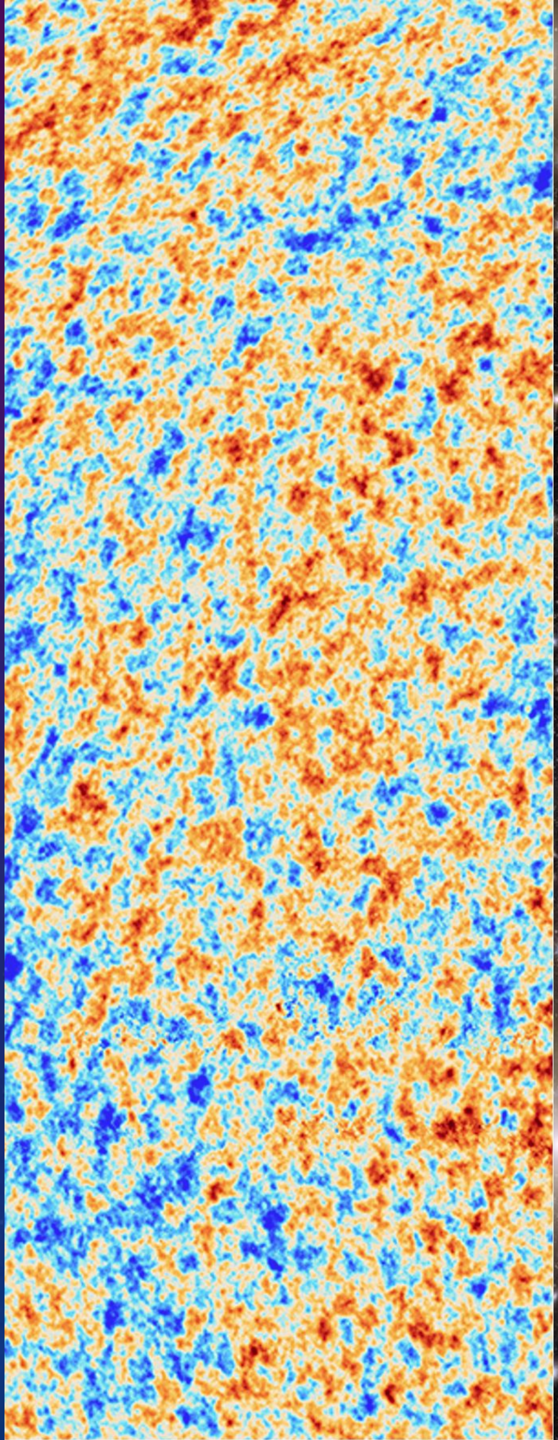
Antonio L. Maroto

IPARCOS-UCM Scientific Advisory Committee
Wednesday, 6 March, 2024

1. RESEARCH LINES

Research Lines

- Inflation and early universe cosmology
- Dark matter models
- Dark energy models
- Modified gravity
- Cosmological model selection
- Extragalactic surveys
- Gravitational waves



1. PERSONNEL OF THE GROUP

Personnel (2022-24)

Senior

José A. R. Cembranos
Antonio L. Maroto
Prado Martín Moruno
Javier Rubio

Postdocs

Clara Álvarez Luna
Jacobo Asorey Barreiro
Javier de Cruz Pérez
Mindaugas Karciauskas
Héctor Villarrubia Rojo

PhD Students

Teodor Borislavov Vasilev
Antonio G. Bello-Morales
Álvaro G. Cendal
Darío Jaramillo Garrido
Alfredo D. Miravet
Álvaro Parra-López
José Jaime Terente Díaz

MSc Students

Mikel Artola Pérez
Pablo García Sabariego
Victor Lopez Oller
Jesús Luque del Castillo
Javier Ortega del Río
Cristóbal Sánchez Moreno
Carlos Soler Vicente
Diego Tessainer Bonet
Víctor Viciach Gallego

Measurements to reduce gender imbalance:

- Promotion of the area for MSc and undergraduate students.
- Bachelor thesis.
- Collaboration in activities promoting vocations in STEM.

AMIT MADRID

2. FUNDING

Projects

- A.L. Maroto and J.A.R. Cembranos, “*Cosmology, Astrophysics and Gravitation of the dark sector*” PID2019-107394GB-I00
- Rubio J. y Ruiz Cembranos J.A.; *“Building the Universe: From inflation to Dark Matter” (BuildingUniverse),* PID2022-139841NB-I00.
- A.L. Maroto and M. P. Martín Moruno, “Cosmology and gravitation of the dark sector” (DarkSector), PID2022-138263NB-I00.
- J. Asorey, “*Cosmología con cartografiados extra-galácticos de radio con precursores del Squre Kilometre Array Observatory*” UCM-PR3/23-30808.

Participation in COST actions

- “Quantum gravity phenomenology in the multi-messenger approach” (QG-MM): 13/11/2018-13/09/2023.
- “Addressing observational tensions in cosmology with systematics and fundamental physics” (CosmoVerse): 21/10/2022-20/10/2026.
- “COSMIC WISPers in the Dark Universe: Theory, astrophysics and experiments” (CosmicWISPers): 03/10/2022-02/10/2026.

3. COLLABORATIONS

COLLABORATIONS

FREQUENT COLLABORATORS

VNiVERSiDAD D SALAMANCA

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

SEJONG UNIVERSITAS
AGAPE
1940
CREATIVITAS SERVITIUM

IPhT SACLAY

Technical University of Munich
TUM

NYU

TÉCNICO LISBOA

KASI

Ciemat

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

LSU
LOUISIANA STATE UNIVERSITY

VICTORIA
UNIVERSITY OF WELLINGTON
TE WHARE WĀNANGA
O TE ŪPOKO O TE IKA A MĀUI

4. SCIENTIFIC RESULTS

(DURING THE PAST 2 YEARS)

ARTICLES (2022)

1. “*Toy models for hierarchy studies*”, C. Álvarez-Luna, J.A.R. Cembranos, J.J. Sanz-Cillero, European Physical Journal C (2022) Vol. 82, Núm. 11.
2. “*Quintessential Inflation: A Tale of Emergent and Broken Symmetries*”, D. Bettoni, J. Rubio, *Galaxies* 10 (2022) 22.
3. “*Hubble-induced phase transitions on the lattice with applications to Ricci reheating*”, D. Bettoni, A. Lopez-Eiguren, J. Rubio, *JCAP* 01 (2022) 01, 002.
4. “*Higgs-Dilaton inflation in Einstein-Cartan gravity*”, M. Piani, J. Rubio, JCAP 05 (2022) 05, 009.
5. “*Probing ultra-light axion dark matter from 21 cm tomography using Convolutional Neural Networks”*, C. Sabiu, K. Kadota, J. Asorey, I. Park JCAP (2022) 01, 020.
6. “*Quantum gravity phenomenology at the dawn of the multi-messenger era – A review*”, A. Addazi et al., Prog. Part. Nucl. PHys. 125 (2022) 103948.
7. “*New horizons for fundamental physics with LISA*”, [LISA Collaboration] K. G. Arun, et al., Living Rev. Rel. 25 (2022) 1, 4.
8. “*A measurement of the integrated Sachs-Wolfe effect with the Rapid ASKAP Continuum Survey*”, B. Bahr-Kalus, D. Parkinson, J. Asorey, S. Camera, C. Hale, F. Qin, MNRAS 517 (2022) 3785-3803.
9. “*Vector dark radiation and gravitational-wave polarization*”, A.D. Miravet and A.L. Maroto, JCAP 09 (2022), 014.
10. “Cosmology intertwined: A review of the particle physics, astrophysics and cosmology associated with the cosmological tensions”, E. Abdalla et al. (including J. de Cruz), JHEAp (2022) 49-211.
11. “*Pseudo-Kähler-Einstein geometries”*, C.G. Boiza, J.A.R. Cembranos, Physical Review D (2022) Vol. 105, Núm. 6.
12. “*LHC constraints on hidden gravitons”*, J.A.R. Cembranos, R.L. Delgado, H. Villarrubia-Rojo, Journal of High Energy Physics (2022) Vol. 2022, Núm. 1.
13. “*Causal structure of accelerating black holes*”, J.A.R. Cembranos, L.J. Garay, S.A. Ortega, European Physical Journal C (2022) Vol. 82, Núm. 9.
14. “*Scalar quantum fields in cosmologies with 2+1 spacetime dimensions“,* N. Sánchez-Kuntz, A. Parra-López, M. Tolosa-Simeón, T. Haas, S. Floerchinger PRD 105, 105020 (2022)
15. “*Curved and expanding spacetime geometries in Bose-Einstein condensates*”, M. Tolosa-Simeón, A. Parra-López, N. Sánchez-Kuntz, T. Haas, C. Viermann, M. Sparn, N. Liebster, M. Hans, E. Kath, H. Strobel, M. K. Oberthaler, S. Floerchinger, PRA 106, 033313 (2022)
16. “*Quantum field simulator for dynamics in curved spacetime*”, C. Viermann, M. Sparn, N. Liebster, M. Hans, E. Kath, A. Parra-López, M. Tolosa-Simeón, N. Sánchez-Kuntz, T. Haas, H. Strobel, S. Floerchinger, M. K. Oberthaler, Nature, 10.1038/s41586-022-05313-9 (2022)

ARTICLES (2023)

1. “*On the impact of nonlocal gravity on compact stars*”, G. Panotopoulos, I. Lopes, J. Rubio, Int. J. Mod. Phys. D 32 (2023) 02, 2250139.
2. “*Preheating in Einstein-Cartan Higgs Inflation: oscillon formation*”, M. Piani, J. Rubio, JCAP 12 (2023) 002.
3. “*From Hubble to Bubble*”,M. Kierkla, G. Laverda, M. Lewicki, A. Mantziris, M. Piani, JHEP 11 (2023) 077
4. “*Big rip in shift-symmetric Kinetic Gravity Braiding theories”*, T. Borislavov Vasilev, M. Bouhmadi-López, P. Martín-Moruno, Phys. Lett. B 838 (2023) 13771.
5. “*Phantom attractors in kinetic gravity braiding theories: a dynamical system approach*”, T. Borislavov Vasilev, M. Bouhmadi-López, P. Martín-Moruno, JCAP 06 (2023) 026.
6. “*Graviton-photon oscillation in a cosmic background for a general theory of gravity*”, J. A. R. Cembranos, M. González Ortiz, P. Martín-Moruno, Phys. Rev. D 108 (2023) 10, 104001.
7. “*Gravitational leptogenesis from metric perturbations*”, A. L. Maroto, A.D. Miravet, Phys. Rev. D107 (2023) no.4, 043538
8. *Current data are consistent with flat spatial hypersurfaces in the LCDM cosmological model but favor more lensing than the model predicts*, J. de Cruz Pérez, C-G. Park and B. Ratra, Phys.Rev.D 107 (2023) 6, 063522.
9. *Running vacuum in the universe: Phenomenological status in light of the latest observations and its impact on σ8 and H0 tensions*, J. Solà Peracaula, A. Gómez-Valent, J. de Cruz Pérez and C. Moreno-Pulido, Universe 9 (2023) 6, 262.
10. “*Wehrl entropy of entangled oscillators from the Segal–Bargmann formalism*”, D. Alonso-López, J.A.R. Cembranos, D. Díaz-Guerra, A. Mínguez-Sánchez, European Physical Journal D (2023) Vol. 77, Núm. 3.
11. “*Invisible dilaton*”, P. Brax, C. Burrage, J.A.R. Cembranos, P. Valageas, Physical Review D (2023) Vol. 107, Núm. 9.
12. “*Gravitational Coleman-Weinberg mechanism*”, C. Álvarez-Luna, S. de la Calle-Leal, J.A.R. Cembranos, J.J. Sanz-Cillero, Journal of High Energy Physics (2023) Vol. 2023, Núm. 2.
13. “*Cosmology with the Laser Interferometer Space Antenna*”, P. Auclair… J.A.R. Cembranos,... Living Reviews in Relativity (2023) Vol. 26, Núm. 1.
14. “*Late vacuum choice and slow roll approximation in gravitational particle production during reheating*”, J.A.R. Cembranos, L.J. Garay, A. Parra-López, J.M. Sánchez Velázquez, Journal of Cosmology and Astroparticle Physics (2023) Vol. 2023, Núm. 8.
15. “*Operational realization of quantum vacuum ambiguities*”, A. Álvarez-Domínguez, J.A.R. Cembranos, L.J. Garay, M. Martín-Benito, A. Parra-López, J.M. Sánchez Velázquez, Physical Review D (2023) Vol. 108, Núm. 6

ARTICLES (2024)

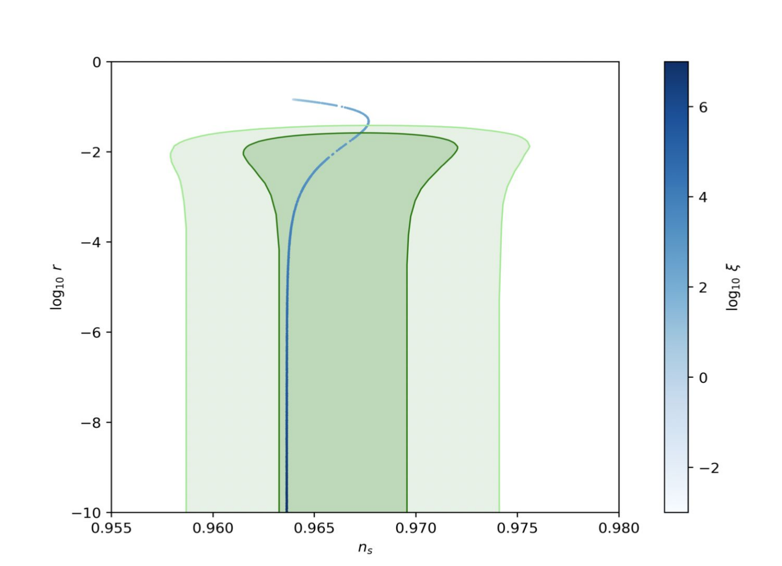
1. *"The geometry of inflationary observables: Lifts, flows, equivalence classes"*, G. K. Karananas, M. Michel, J. Rubio, Phys.Lett.B 850 (2024).
2. *"Observational constraints on early coupled quintessence"*, L.W.K. Goh, J. Bachs-Esteban, A. Gómez-Valent, V. Pettorino, -J. Rubio, Phys.Rev.D 109 (2024) 2, 023530 .
3. *Running vacuum in Brans & Dicke theory: A possible cure for the σ8 and H0 tensions*, J. de Cruz Pérez and J. Solà Peracaula, Phys.Dark.Univ 43 (2024) 101406.
4. *Unified transverse diffeomorphism invariant field theory for the dark sector*, D. Alonso-López, J. de Cruz Pérez and A. L. Maroto, Phys.Rev.D 109 (2024) 2, 023537.
5. "*Vector dark matter production during inflation and reheating*", J.A.R. Cembranos, L.J. Garay, A. Parra-López, J.M. Sánchez Velázquez, Journal of Cosmology and Astroparticle Physics (2024) Vol. 2024, Núm. 2
6. "*Cosmology in gravity models with broken diffeomorphism*", A.G. Bello-Morales and A. L. Maroto, Phys. Rev. D109 (2024), 043506
7. *"TDiff invariant field theories for cosmology"*, A. L. Maroto, arXiv:2301.05713, accepted for publication in JCAP.
8. *"TDiff in the Dark: Gravity with a scalar field invariant under transverse diffeomorphism"*, D. Jaramillo-Garrido, A. L. Maroto, P. Martín-Moruno, arXiv:2307.14861, accepted for publication in JHEP.

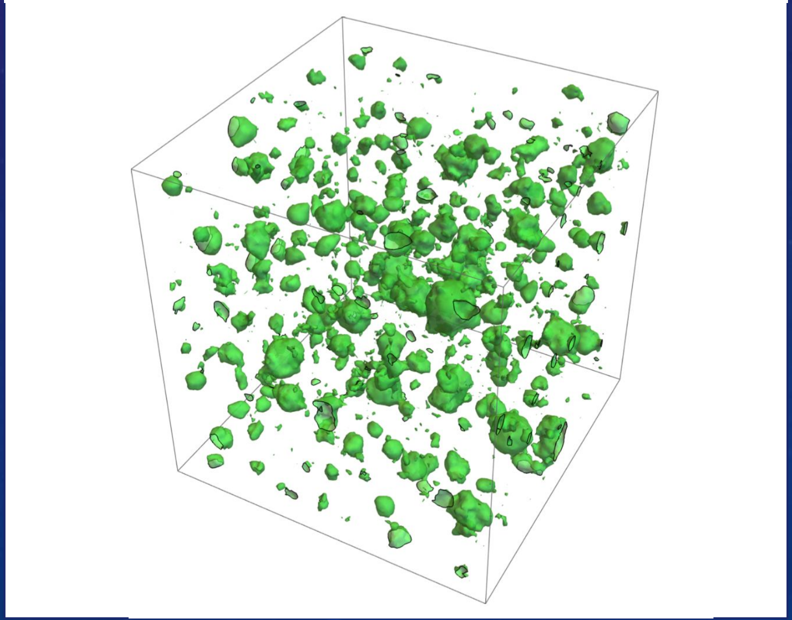
PRE-PRINTS

1. "*Ricci Reheating Reloaded*", G. Laverda, J. Rubio, 2307.03774 [astro-ph.CO]
2. "*Rescuing Gravitational-Reheating in Chaotic Inflation*" B. Barman, N. Bernal, J. Rubio, 2310.06039 [hep-ph]
3. "*The Dark Energy Survey: Cosmology results with 1500 New High-redshift Type Ia Supernovae using the Full 5-year dataset*" DES Collaboration, T. M. C. Abbott et al. (including J. Asorey), 2401.02929 [astro-ph]
4. "*The Dark Energy Survey Supernova Program: Cosmological Analysis and Systematic Uncertainties*" M. Vincenzi et al. (including J. Asorey), 2401.02945 [astro-ph]
5. "*The Rise and Fall of the Standard-Model Higgs: Electroweak Vacuum Stability during Kination*", G. Laverda, J. Rubio, 2402.06000 [hep-ph]
6. "*The Dark Energy Survey: A 2.1% measurement of the angular Baryonic Acoustic Oscillation scale at redshift z_{eff}=0.85 from the final dataset*" DES Collaboration, T. M. C. Abbott et al. (including J. Asorey), 2402.10696 [astro-ph]
7. "*Symmetry restoration for TDiff scalar fields*", D. Jaramillo-Garrido, A.L. Maroto and P. Martín-Moruno, [arXiv:2402.17422 [gr-qc]].
8. "*TDiff invariant gauge fields in cosmology*", A.L. Maroto and A.D. Miravet, [arXiv:2402.18368 [gr-qc]].

GRAVITATIONAL INCARNATIONS OF HIGGS INFLATION

- Among the plethora of inflationary models, Higgs Inflation stands out as a minimal scenario, not requiring new degrees of freedom beyond the Standard Model.
- The inclusion of a non-minimal coupling of the Higgs field to gravity provides also an indirect way of testing the fundamental nature of gravity, breaking the well-known equivalence of pure metric-affine gravitational theories.
  - We studied the phenomenology of a scale-invariant extension of Higgs inflation in the context of Einstein-Cartan gravity, focusing on the separate impact of the Holst and Nieh-Yan terms on the inflationary observables and identifying an additional attractor solution.
  - We made use of 3+1 classical lattice simulations to study the preheating stage of Higgs Inflation in Einstein-Cartan gravity, demonstrating the formation of oscillon configurations leading to a prolonged period of matter domination and a significant gravitational wave signal.



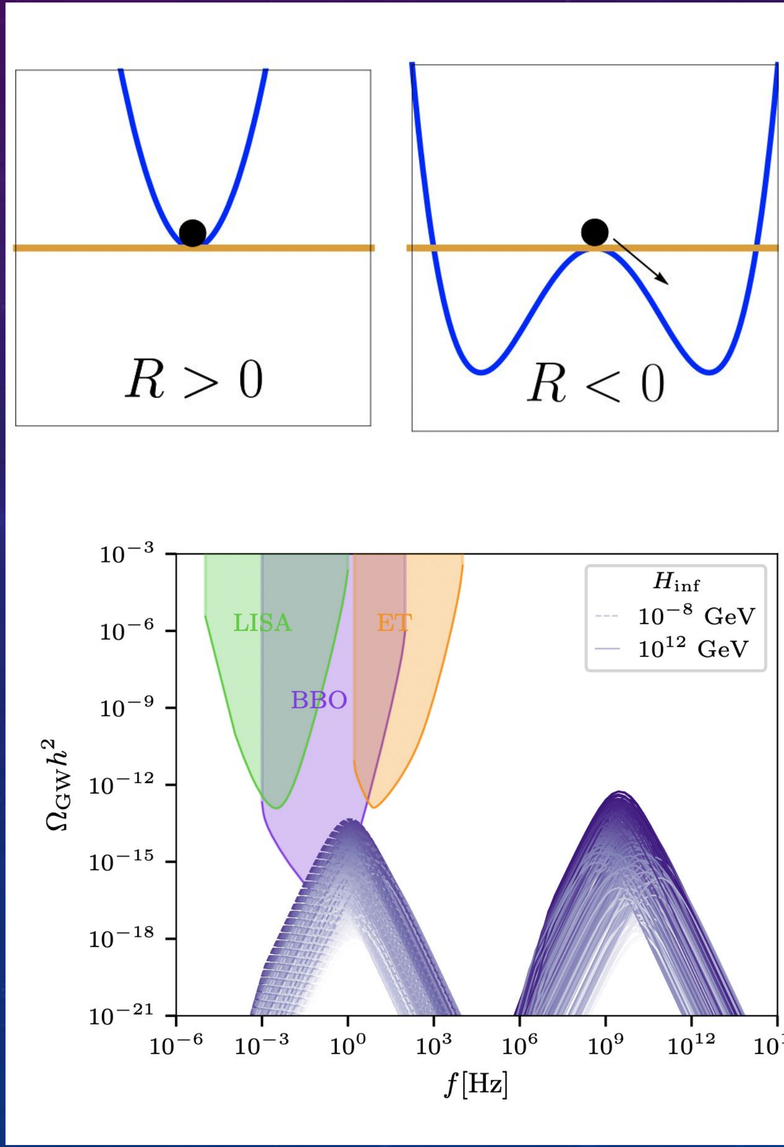


"Higgs-Dilaton inflation in Einstein-Cartan gravity", M. Piani, J. Rubio, JCAP 05 (2022) 05, 009.
"Preheating in Einstein-Cartan Higgs Inflation: oscillon formation", M. Piani, J. Rubio, JCAP 12 (2023) 002.

HUBBLE-INDUCED PHASE TRANSITIONS

- The combination of non-minimal couplings to gravity with the post-inflationary kinetic-dominated era typically appearing in quintessential inflation scenarios may lead to the spontaneous symmetry breaking of internal symmetries and its eventual restoration at the onset of radiation domination.
- On general grounds, the breaking of these symmetries leads to the creation of particles, topological defects and gravitational waves until the symmetry is restored.

  - We performed a comprehensive characterization of Hubble-induced transitions as a reheating mechanism, deriving a set of ready-to-use parametric formulas characterizing the onset of radiation domination.
  - We investigated whether a variation of this triggering mechanism can lead to a strong first-order phase transition with gravitational wave's signatures potentially accessible with future detectors.



"Hubble-induced phase transitions on the lattice with applications to Ricci reheating", D. Bettoni, A. Lopez-Eiguren, J. Rubio, *JCAP* 01 (2022) 01, 002.
"Ricci Reheating Reloaded", G. Laverda, J. Rubio, 2307.03774 [astro-ph.CO]
"From Hubble to Bubble", M. Kierkla, G. Laverda, M. Lewicki, A. Mantziris, M. Piani, JHEP 11 (2023) 077

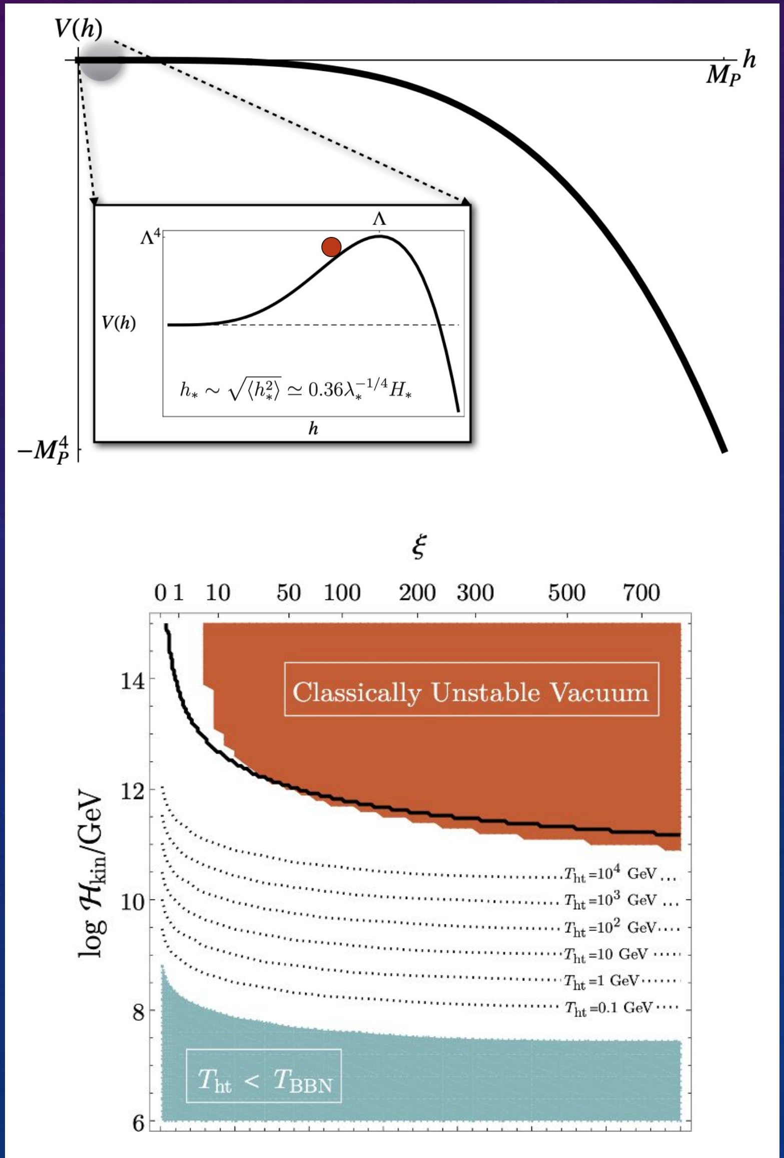
ELECTROWEAK VACUUM STABILITY AFTER INFLATION

- The electroweak vacuum we live in might not be absolutely stable, as the Higgs self-coupling may become negative at high energies.

- Whether the EW vacuum is stable or not offers the chance to link together the fundamental couplings in the SM and the parameters of early-Universe cosmology.

  - We investigated the EW vacuum stability of the non-minimally coupled Standard-Model Higgs during a phase of kinetic domination following the end of inflation, setting significant constraints on the top mass, the scale of inflation and the strength of the non-minimal coupling.

  - If we task the Higgs with heating the post-inflationary Universe, further regions of the parameter space can be excluded.



"The Rise and Fall of the Standard-Model Higgs: Electroweak Vacuum Stability during Kination", G. Laverda, J. Rubio, 2402.06000 [hep-ph]

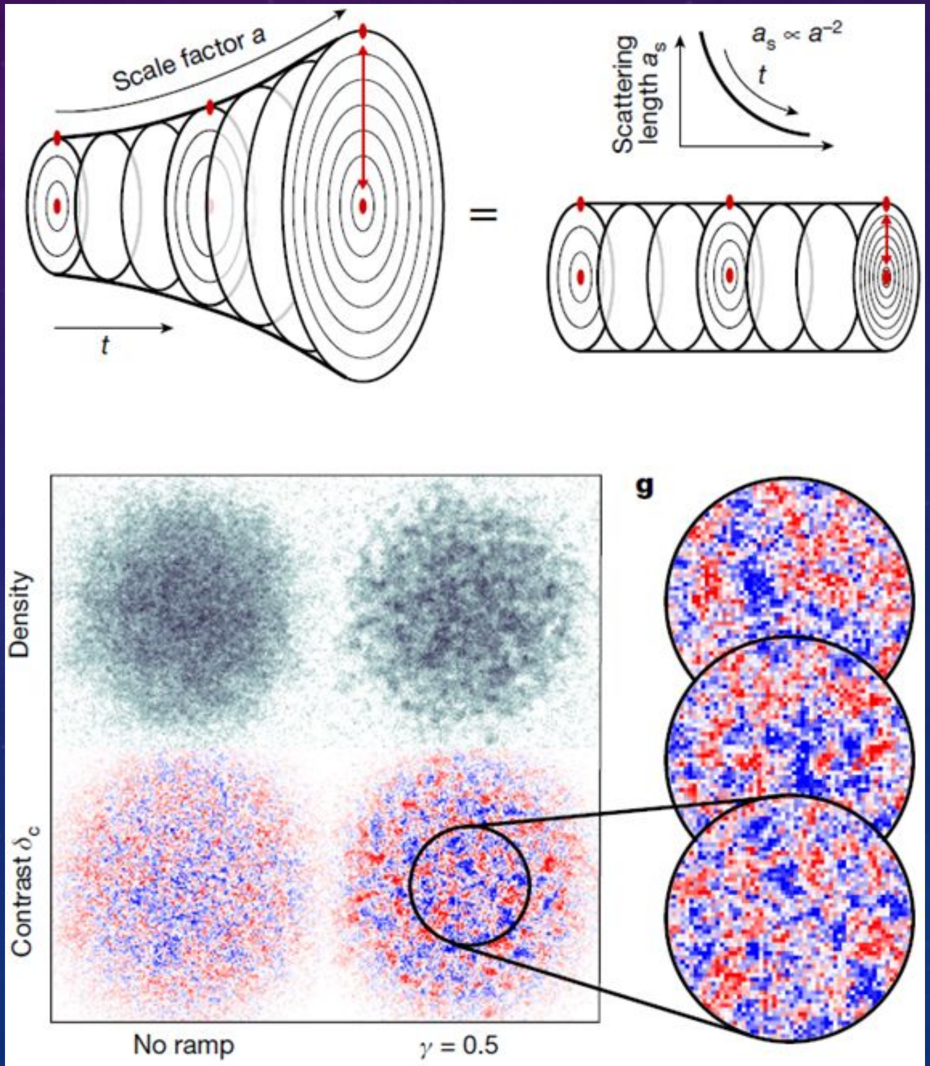
GRAVITATIONAL PARTICLE PRODUCTION

- ❖ Production of particles out of the vacuum in a time-dependent geometry is inherent to quantum field theory in curved spacetime
- ❖ This mechanism affects all non-conformally coupled fields, and therefore is particularly interesting in the context of Dark Matter
- ❖ The observed abundance of Dark Matter can be understood to have a gravitational origin, constraining its properties

“Vector dark matter production during inflation and reheating”, J.A.R. Cembranos, L.J. Garay, A. Parra-López, J.M. Sánchez Velázquez, Journal of Cosmology and Astroparticle Physics (2024) Vol. 2024, Núm. 2

- ❖ Gravitational particle production can be simulated in analog gravity experiments, allowing the study of properties such as entanglement
- ❖ Experimental realization of cosmological pair production in a Bose-Einstein condensate in collaboration with the University of Heidelberg

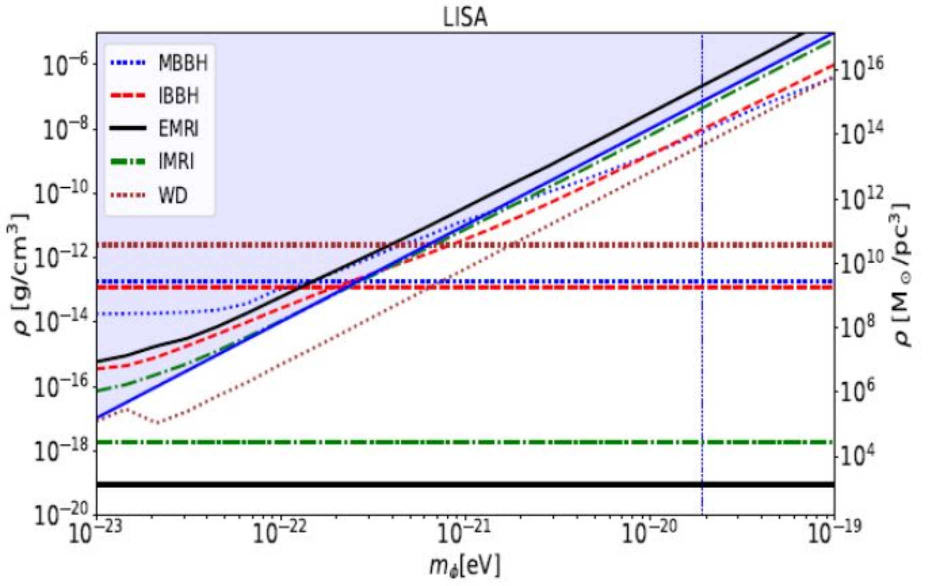
“Quantum field simulator for dynamics in curved spacetime”, C. Viermann, M. Sparn, N. Liebster, M. Hans, E. Kath, A. Parra-López, M. Tolosa-Simeón, N. Sánchez-Kuntz, T. Haas, H. Strobel, S. Floerchinger, M. K. Oberthaler, Nature, 10.1038/s41586-022-05313-9 (2022)



ULTRALIGHT DARK MATTER

- ❖ The exploration of dark matter (DM) halos as scalar field solitons of extended sizes has emerged as a promising avenue to test the fundamental nature of DM. Recent studies have investigated this possibility as an alternative framework addressing some of the small-scale observational challenges of the conventional Cold DM scenario.
- ❖ Although these oscillations manifest themselves at rapid rates on cosmological and astrophysical scales, a common analytical strategy involves integrating them out, focusing on the slow temporal and spatial variations in the amplitude of the scalar field for a more manageable analysis.
- ❖ DM models, distinguished by a background oscillating field whose pulsation is determined by the mass of the scalar particle, introduce a novel perspective on the dynamics of DM.
- ❖ This has sparked extensive research into the dynamics of Ultralight DM solitons, also known as cores, within halos.

  - ➢ we have considered scalar field solitons and their influence on astrophysical phenomena, in particular the propagation of gravitational waves. Detecting dark matter oscillations with gravitational waveforms.
  - ➢ “Detecting dark matter oscillations with gravitational waveforms”, Philippe Brax(IPhT, Saclay), Clare Burrage(Nottingham U.), Jose A.R. Cembranos(UCM, Somosaguas), Patrick Valageas(IPhT, Saclay) (Feb 7, 2024) e-Print: 2402.04819 [astro-ph.CO]



DARK ENERGY IN SHIFT-SYMMETRIC KINETIC GRAVITY BRAIDING THEORIES

- ❖ A scalar field is a simple fundamental description for dark energy.
- ❖ Shift symmetry leads to kinetic-driven dark energy and avoid fine-tuning problems: $\phi \Rightarrow \phi + c$
- ❖ A shift-symmetric field with a canonical kinetic term describes a stiff fluid in GR.
  - ➢ Generalizing the kinetic term: the most general shift-symmetric scalar-field theory leading to gravitational waves propagating at the speed of light is shift-symmetric KGB.

$$S_\phi = \int d^4x\sqrt{-g}[K(X) - G(X)\Box\phi]$$

  - ➢ Importance of defining the autonomous system in terms of compact variables in order to describe all possible future cosmic evolutions.
  - ➢ The dynamical system analysis of this theory has shown that our Universe does not necessarily evolve to a quasi-de Sitter stage (big rip, big freeze,...).
  - ➢ We have analysed in detail the stability of dark energy models in this framework.

Work in the context of the PhD thesis of Teodor Borislavov Vasilev.

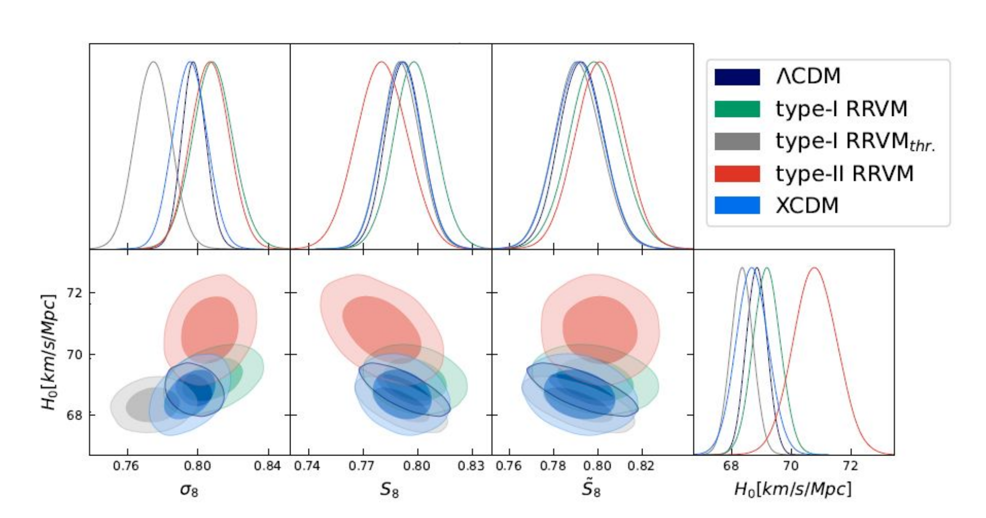
"Big rip in shift-symmetric Kinetic Gravity Braiding theories", T. Borislavov Vasilev, M. Bouhmadi-López, P. Martín-Moruno, Phys. Lett. B 838 (2023) 13771. "Phantom attractors in kinetic gravity braiding theories: a dynamical system approach", T. Borislavov Vasilev, M. Bouhmadi-López, P. Martín-Moruno, JCAP 06 (2023) 026. "Dark energy with a shift-symmetric scalar field: obstacles, loophole hunting and dead ends", T. Borislavov Vasilev, M. Bouhmadi-López, P. Martín-Moruno, in preparation.

RUNNING VACUUM IN THE UNIVERSE

- We study the possibility that the vacuum energy density is a dynamical quantity whose evolution is motivated in the context of QFT in curved space time

$$\rho_{\rm vac}(H) = \frac{3}{8\pi G_N}\left(c_0 + \nu H^2 + \alpha \dot{H}\right) + \mathcal{O}(H^4)\,.$$

- Two different scenarios are considered
  - The vacuum can be running at the expense of exchanging energy with the dark matter.
  - Matter is strictly conserved but we allow for the running of the gravitational coupling.
- A mild dynamics of the cosmic vacuum is favored by the observational data which results in loosening the σ_8 and H_0 tensions.



Running vacuum in the universe: Phenomenological status in light of the latest observations and its impact on σ_8 and H_0 tensions, J. Solà Peracaula, A. Gómez-Valent, J. de Cruz Pérez and C. Moreno-Pulido, Universe 9 (2023) 6, 262.

TDiff INVARIANT FIELD THEORIES IN COSMOLOGY

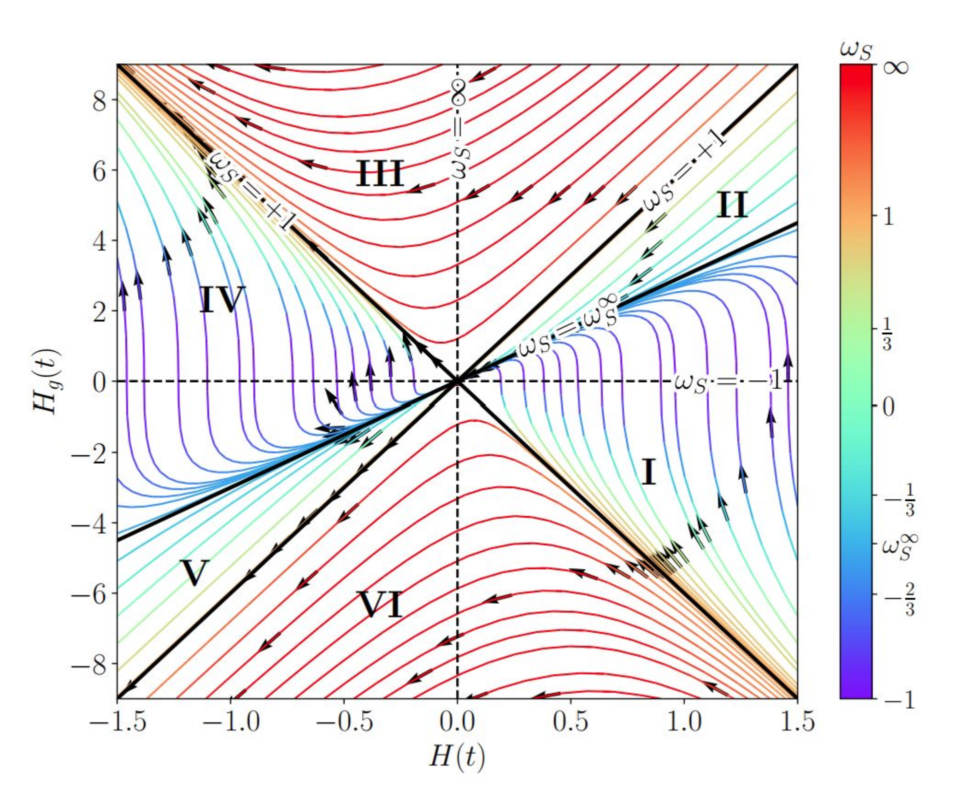
- We consider models which break Diff symmetry down to TDiff either in the **gravitational sector** or in the **couplings to matter.**

- In the **gravitational sector,** we consider models which propagate an additional TDiff scalar graviton

$$S = -\frac{1}{16\pi G}\int d^4x\sqrt{g}\left(R - \frac{a_5}{4} g^{\mu\nu}(\partial_\mu \ln g)(\partial_\nu \ln g)\right)$$

- In the **couplings to matter,** we consider

$$S_\phi = \int d^4x\,\mathcal{L} = \int d^4x \left(\frac{f_K(g)}{2} g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - f_V(g)V(\phi)\right)$$



“*Cosmology in gravity models with broken diffeomorphism*”, A.G. Bello-Morales and A. L. Maroto, Phys. Rev. D109 (2024), 043506“*TDiff invariant field theories for cosmology*”, A. L. Maroto, arXiv:2301.05713, accepted for publication in JCAP. “*TDiff in the Dark: Gravity with a scalar field invariant under transverse diffeomorphism*”, arXiv:2307.14861, D. Jaramillo-Garrido, A. L. Maroto, P. Martín-Moruno, accepted for publication in JHEP. “*Symmetry restoration for TDiff scalar fields*”, D. Jaramillo-Garrido, A.L. Maroto and P. Martín-Moruno, [arXiv:2402.17422 [gr-qc]]. “*TDiff invariant gauge fields in cosmology*”, A.L. Maroto and A.D. Miravet, [arXiv:2402.18368 [gr-qc]].

UNIFIED TDiff MODEL FOR THE DARK SECTOR

- ❖ We consider a minimally coupled scalar field with an action that only contains a kinetic term and is invariant under TDiff transformations.

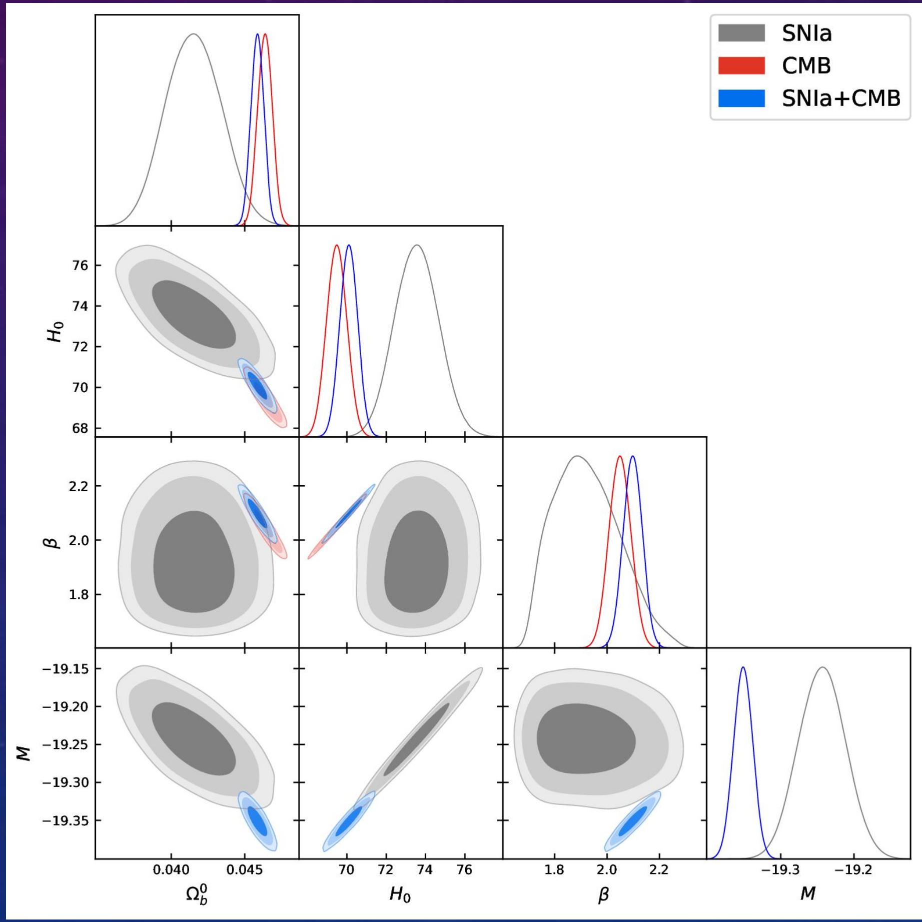
$$S_\phi = \int d^4x f(g) \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

- ❖ With the function $f(g) = e^{-\beta g}$ of the metric determinant it is possible to model both dark matter and dark energy with a single scalar field.

- ❖ The equation of state interpolates between a matter-type behavior at early times and a cosmological constant-type one at late times

$$\omega_\phi = \frac{-\beta g}{1 + \beta g}$$

- ❖ When testing again the CMB+BAO+SNIa+H(z) background data the model is able to improve the performance of the LCDM and alleviate the H_0-tension.



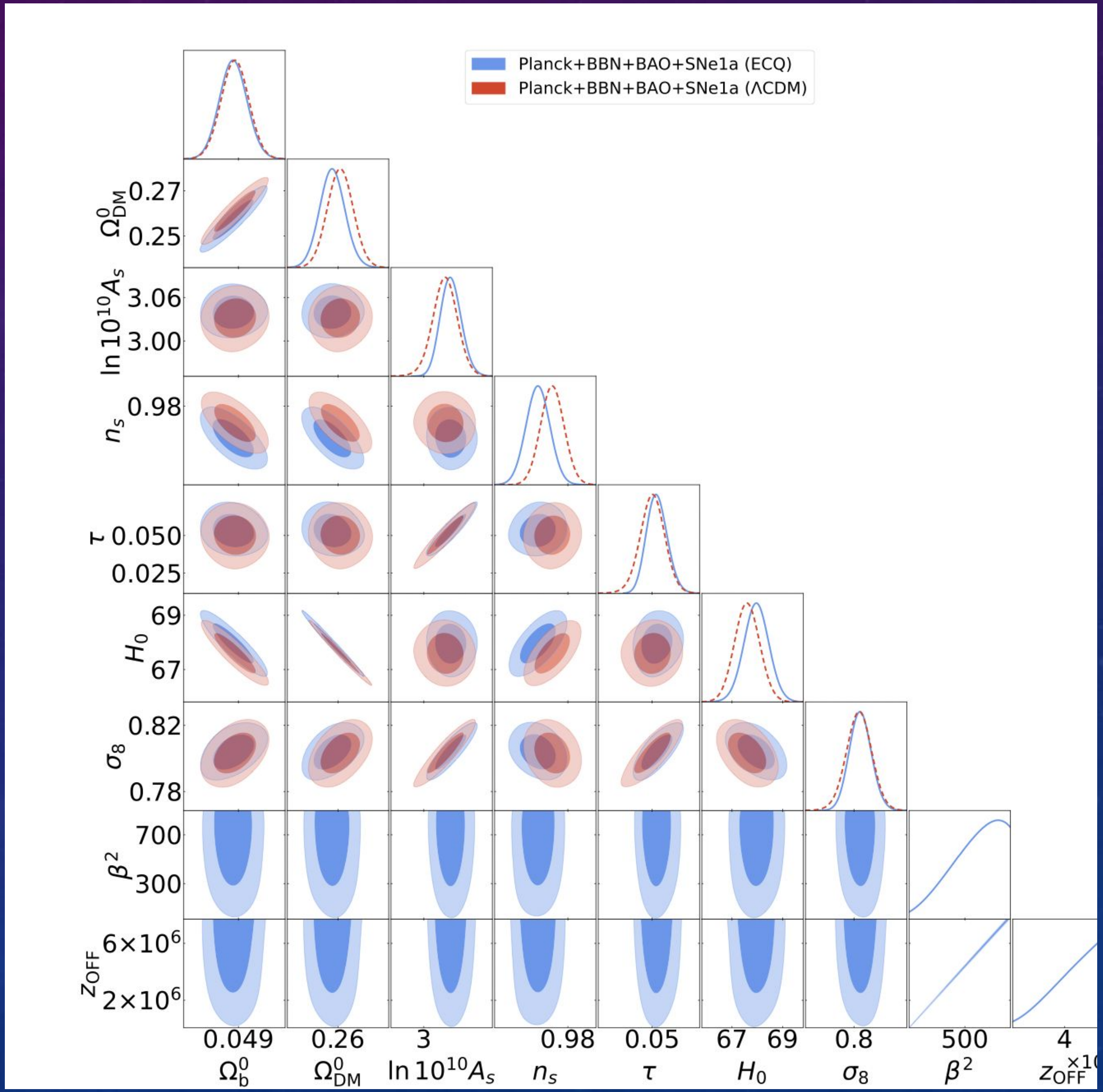
Unified transverse diffeomorphism invariant field theory for the dark sector, D. Alonso-López, J. de Cruz Pérez and A. L. Maroto, Phys.Rev.D 109 (2024) 2, 023537.

FIFTH FORCES BEFORE MATTER-RADIATION EQUALITY

- The existence of long-range attractive forces stronger than gravity can lead to the growth of structure prior to matter domination.

  - We performed a detailed analysis of an early coupled quintessence model with two BSM components: a fermionic DM field interacting through a fifth force stronger than gravity, and a light scalar particle – the interaction mediator – which can play the role of DE.

  - Using CMB, SN1a, BAO, and BBN cosmological data to constrain the strength of fifth force and the redshift at which this interaction becomes effectively inactive.



"Observational constraints on early coupled quintessence", L.W.K. Goh, J. Bachs-Esteban, A. Gómez-Valent, V. Pettorino, -J. Rubio, Phys.Rev.D 109 (2024) 2, 023530

THE LENSING ANOMALY

- The trajectories of the CMB photons are bent by the gravitational of inhomogeneities present in the mass distribution along their way to us.

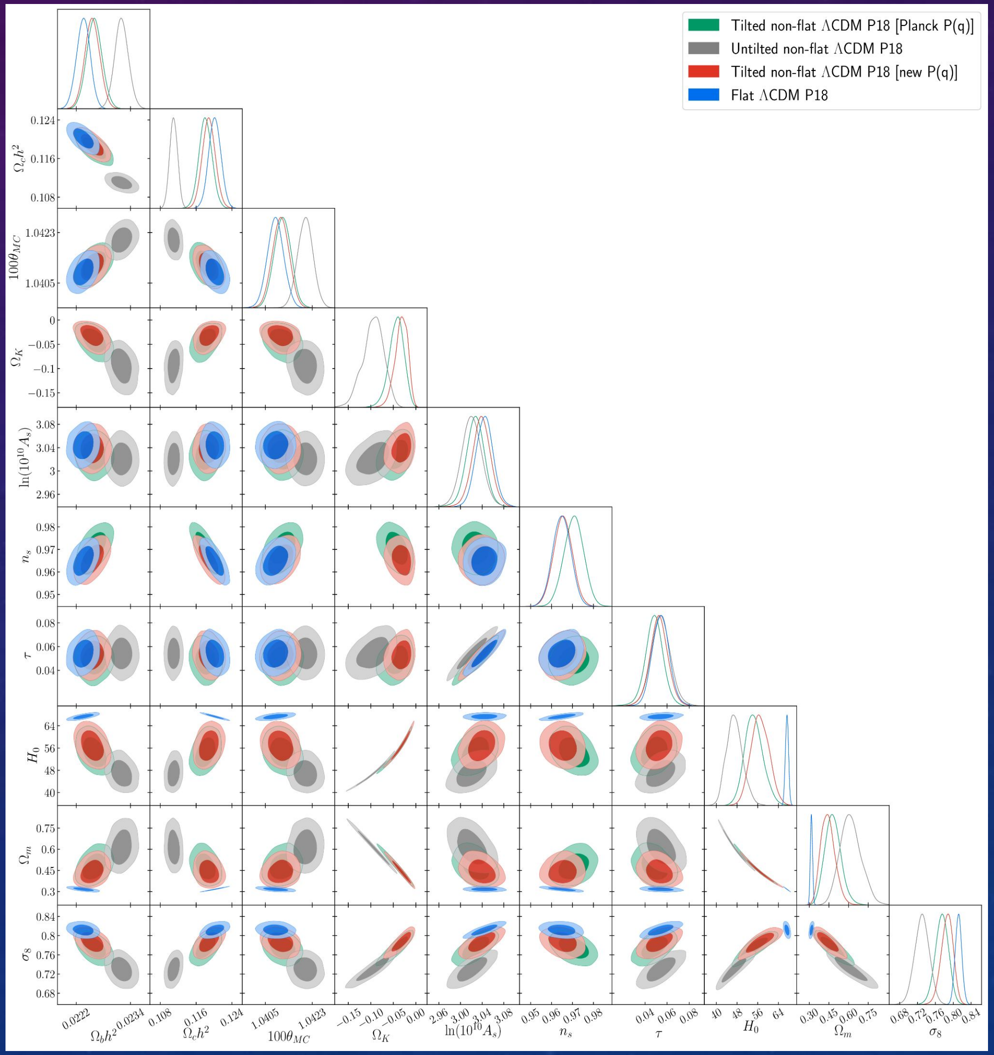
- An excess of CMB weak lensing is observed in the CMB power spectra, compared to what is expected in the LCDM.

Some possible solutions

- Modifications of the primordial power spectrum with a curvature component Ω_k.
- Re-scaling the gravitational potential power spectrum with a phenomenological parameter A_L.

- We test the performance of several models using CMB, BAO, SNIa, H(z) and LSS data being the favored options $\Omega k < 0$ and A_len >1.

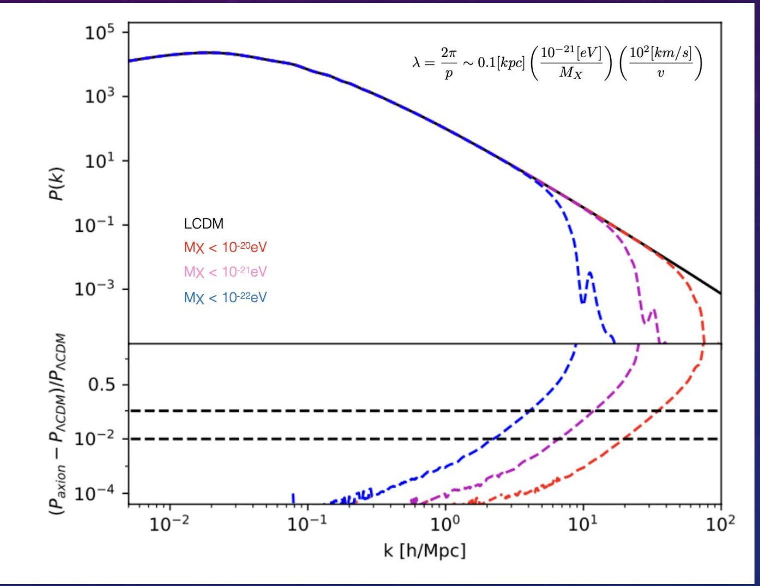
Current data are consistent with flat spatial hypersurfaces in the LCDM cosmological model but favor more lensing than the model predicts, J. de Cruz Pérez, C-G. Park and B. Ratra, Phys.Rev.D 107 (2023) 6, 063522.



RADIO COSMOLOGY

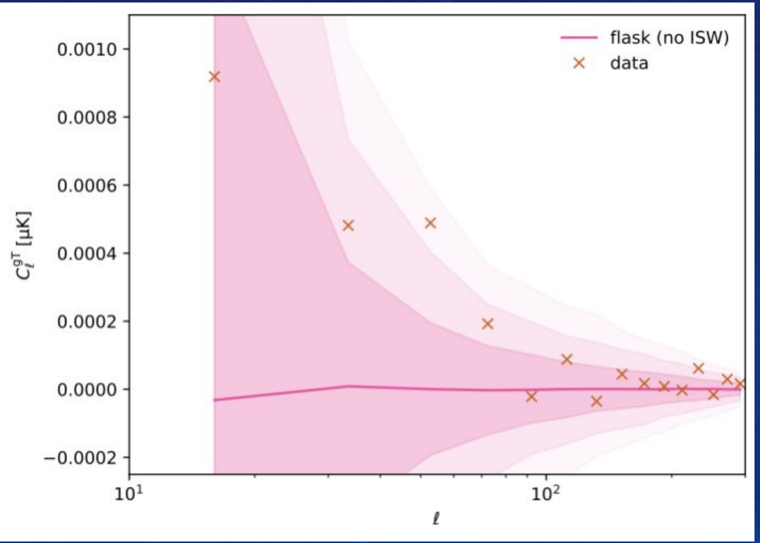
- ❖ The use of radioastronomy for extragalactic observations is a rising field as we will be able to sample new observables and unreached redshifts
- ❖ The observation of intensity maps of 21cm line emission at high redshift allows us to directly constrain models of dark matter such as ultra-light axions or fuzzy dark matter by using CNN to predict reionization redshift (dependent on particle mass).

"Probing ultra-light axion dark matter from 21 cm tomography usinc Convolutional Neural Networks ", C. Sabiu, K.. Kadota, J. Asorey, I. Park, JCAP (2022) 01, 20



- ❖ The ASKAP telescope is one of the largest telescopes of radio continuum and the Rapid ASKAP Continuum Survey (RACS) covered 75% of the sky at a depth of mJy.
- ❖ Using the correlation of the density of radio galaxies from RACS and Planck CMB temperature maps at 2.3 sigma (conservative) and 2.8 (optimistic) which probes the universe is in a non-matter dominated era.

"A measurement of the Integrated Sachs-Wolfe effect with the Rapid ASKAP Continuum Survey", B. Bahr-Kalus, D. Parkinson, J. Asorey, S. Camera, C. Hale, F. Qin MNRAS 517 (2022) 3785 - 3803

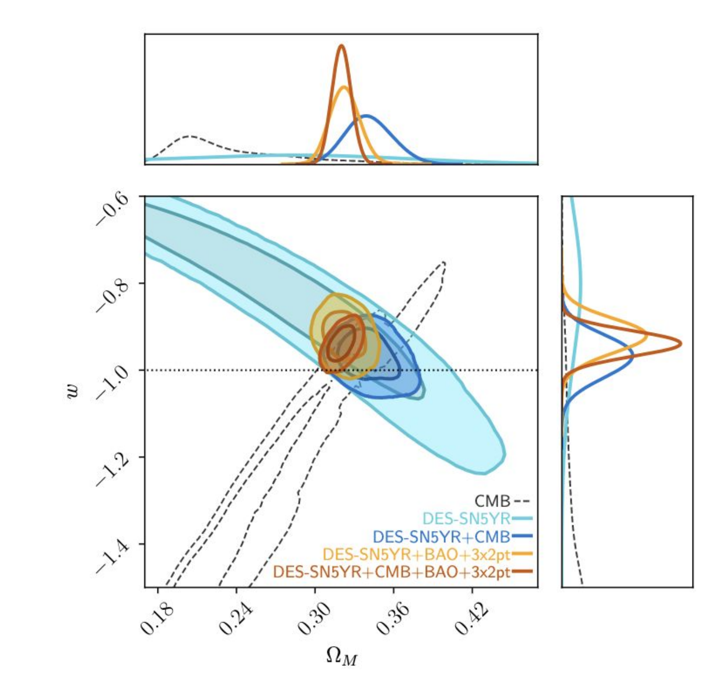


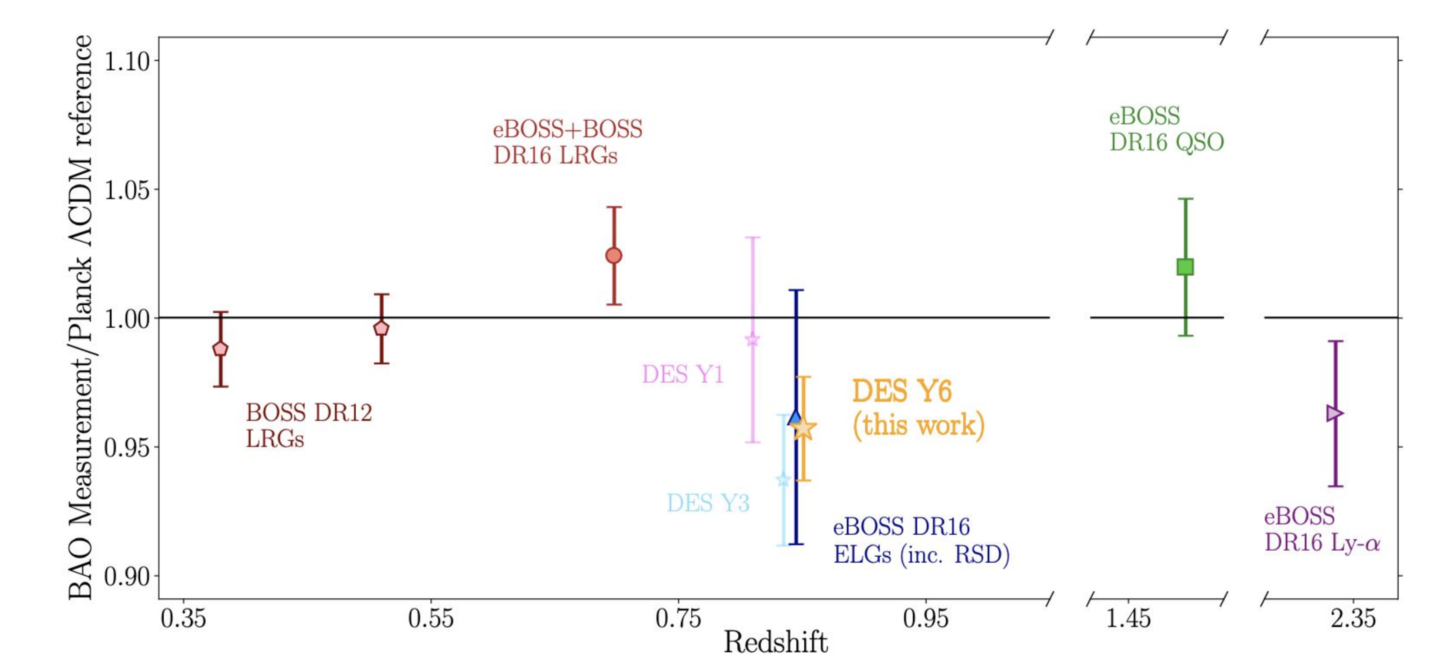
DARK ENERGY SURVEY (DES)

- Final results on type Ia SN Cosmology and BAO measurements from Dark Energy Surcey 6 years of data.

- In “The Dark Energy Survey: Cosmology results with 1500 New High-redshift Type Ia Supernovae using the Full 5-year dataset” DES Collaboration, T. M. C. Abbott et al. (including J. Asorey), arXiv:2401.02929 use of 1635 photometrically classified type Ia Supernovae (largest sample) to validate LCDM model. Dark Energy always consistent with the dataset within 2-sigma.

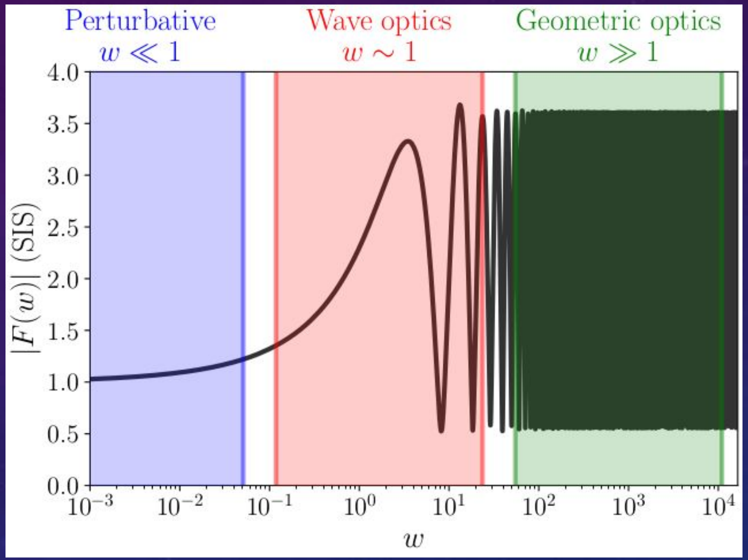
- In “The Dark Energy Survey: A 2.1% measurement of the angular Baryonic Acoustic Oscillation scale at redshift z_{eff}=0.85 from the final dataset” DES Collaboration, T. M. C. Abbott et al. (including J. Asorey), arXiv:2402.10696, DES provides a 2.1% BAO measurement, being the most precise from Stage III surveys at redshifs > 0.75. The measurement is 2.1-sigma below the Planck LCDM predicted BAO theory.



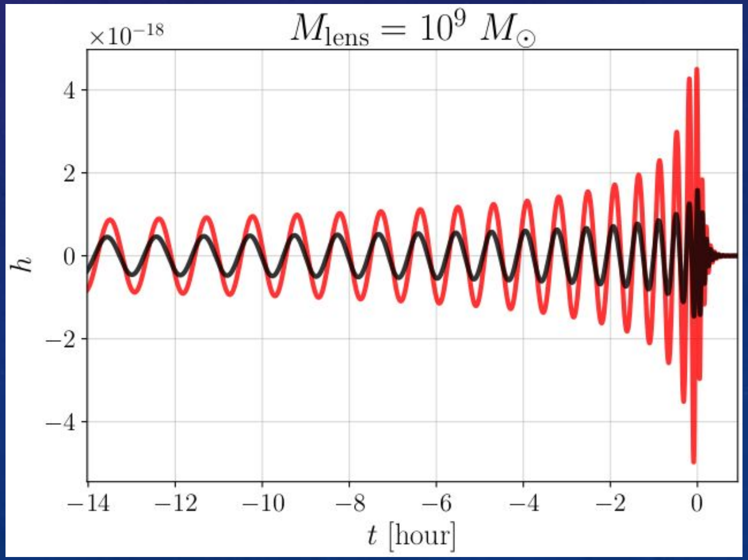


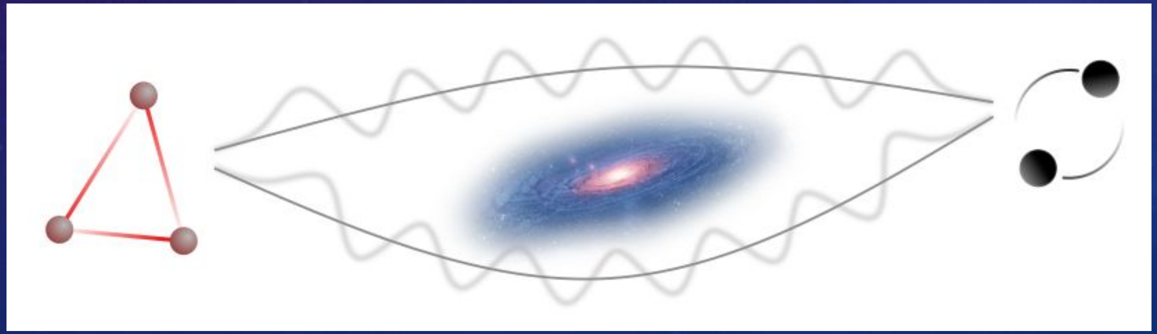
GRAVITATIONAL WAVE LENSING

- Gravitational waves (GWs) can be lensed by matter during their propagation.
- Due to their low frequency, wave optics effects are important and complement electromagnetic observations, always in the geometric optics regime.
- Both strong and weak lensing is observable in GW events and it is sensitive to the substructure of the lens (e.g. existence of cores in halos).
- Weak lensing by low-mass halos will likely be present in LISA events.
- Strongly lensed and microlensed events are guaranteed with the ET.



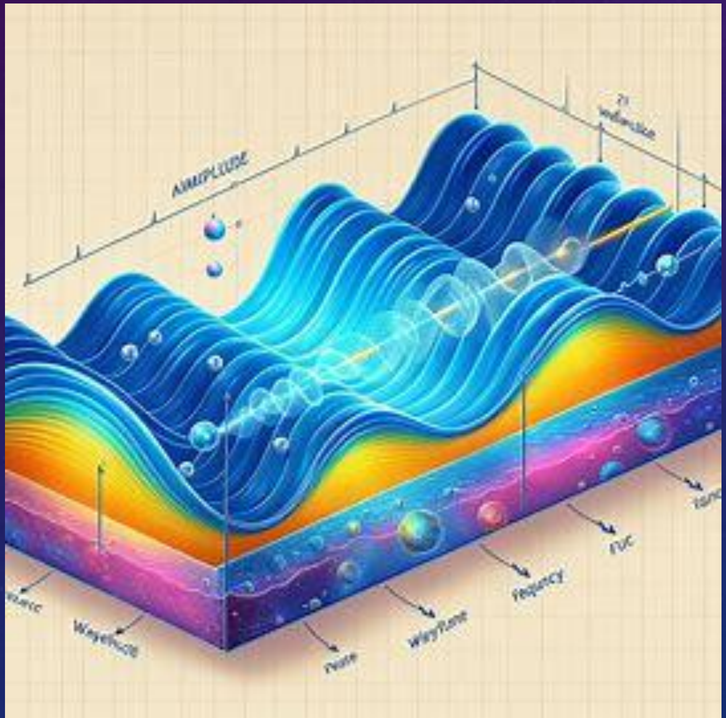
“Weakly lensed gravitational waves: Probing cosmic structures with wave-optics features”, S. Savastano, G. Tambalo, H. Villarrubia-Rojo, M. Zumalacárregui, Physical Review D 108 (2023) 10, 103532





GRAVITON-PHOTON OSCILLATION IN A COSMIC BACKGROUND

- EMWs propagating through an electric or magnetic field generate GWs and viceversa: **graviton-photon oscillation**.
- Alternative theories of gravity should also predict the propagation of GWs in order to be viable alternatives to GR (probably with other modes of gravitational radiation).
- The additional degrees of freedom typically introduced by an alternative theory of gravity can be understood as forming a ***diagravitational medium*** for GWs.



- We had studied in the past how this ***diagravitational medium*** affects the phenomenon of graviton-photon oscillations.
- We have extended our previous study to more generic theories (which could lead to imaginary refractive indexes) and to a cosmic background.
- We have concluded that the mixing probability has a strong dependence on the attenuation term of that refractive index (produced in f(R) gravity, non-local theories,...)

“Graviton-photon oscillation in a cosmic background for a general theory of gravity”, J. A. R. Cembranos, M. González Ortiz, P. Martín-Moruno, Phys. Rev. D 108 (2023) 10, 104001.